Thesis points of doctoral (PhD) dissertation

System supervision and abnormality detection through multivariate statistical methods

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1. Motivations and goals

My doctoral research was concerned with the development of multivariate statistical methods for anomaly and fault detection, with the aim of partially addressing current problems in fault detection and isolation. In parallel with industrial development, the demands placed on technological systems have become more stringent, both in terms of safety engineering and quality. Unexpected production stoppages or quality degradation due to system failures have become unacceptable events. Consequently, maintaining safe and proper operation of industrial systems has become a key issue, one of the pillars of which is the timely and accurate detection of system failures. System failures are symptomatic events whereby process variables in a system are driven outside their intended ranges, as defined by the operators, by some failure root cause. The detection of the presence of fault events and the identification of the root causes of faults is the task of the fault detection and isolation system. Fault detection methods mostly use a posteriori process models or data-based techniques to detect the presence of anomalies. Fault detection systems should operate in a way that allows for the immediate detection of unsafe, process-inappropriate operating conditions, while at the same time being able to distinguish between minor faults, noise and disturbances in the data, so as not to overload system operators with unnecessary alarms. My doctoral research has focused on the further development of data-driven multivariate statistical process monitoring methods for fault detection and isolation aided by the design of new algorithms. I proposed solutions to partially address current issues in the fault detection framework, including the incorporation of process risk into fault detection and the development of fault detection methods for distributed parameter systems.

2. Thesis points

I. I developed a methodology to enable fault isolation in dynamical systems using trajectory distance metrics and justified its applicability under a wide range of operating conditions within dynamic systems.

1. I used dynamic principal component analysis as a base fault detection method to analyze system behavior and pinpoint abnormalities in technological units. I fine-tuned the method for various operating states of the system and evaluated the accuracy of the model.
2. I recorded characteristic dynamic behavior of the system under different faults and observed trajectory data of fault responses in state space. I explored the dissimilarity of the fault trajectories and drew conclusions about the isolability of fault types.
3. I utilized the discrete Fréchet distance metric to compare new fault signals to the established fault library for fault isolation. I observed the isolation capabilities of the method under a wide scope of differing operation conditions. I concluded that the method was able to accurately distinguish the faults under operating conditions in the ±20 % interval compared to their steady state values, with a macro averaged F1 score of above 0.99.

Related publications: 3

II. **I confirmed that a methodology combining risk assessment with fault detection techniques for risk-based system supervision could be successfully applied to minimize superfluous alarm rates in technological systems.**

1. I developed a framework for combining Bayesian networks with failure mode and effect analysis and the results of dynamic principal component analysis for risk-based fault detection.
2. I developed a modified, dynamic risk priority number which utilizes missed alarm rate of failures evaluated through dynamic principal component analysis, failure probability based on Bayesian networks and expert knowledge to characterize risk level of process states.
3. I utilized the modified risk priority number to categorize process abnormalities into classes which warrant alarms and those which only warrant warnings. Through these classes, the operators' ability to judge whether a process failure requires immediate response or not is increased. Using a case study of both a three-tank benchmark system and a dehydrogenation reactor, I concluded that the alarm rate was decreased by 20-30 % alleviating the pressure alarm floods exert on operators.

Related publications: 4, 5

III. **I proved that compartment models can be used to generate data to train fault detection algorithms at reduced computational cost while retaining acceptable performance of the fault detection method.**

1. I investigated the methods of developing compartment models using the results of computational fluid dynamics methods in a rigorous manner.
2. I utilized fuzzy logic to describe the transport phenomena in a complex system through a network of idealized models and accurately approximate system responses. I validated a compartment model and computational fluid dynamics model using experimental data obtained through a laboratory scale mixing tank.
3. I utilized the compartment model to develop a fault detection scheme for the mixing tank and compared its fault detection performance with a fault detection scheme based on data gathered from computational fluid dynamics methods. I found that the fault detection scheme based on the compartment model could be established with 95 % less computational time than the one based on computational fluid dynamics at a cost of an increase of 16 % in missed alarm rate metrics and negligible false alarm rate metric increase. I concluded that the method could be used to accurately approximate the spatio-temporal system responses and used to train fault detection methods with acceptable performance at a significantly decreased computational cost.

Related publications: 1, 2, 6

3. Application possibilities

In my doctoral research, I presented algorithms developed to address the challenges of fault detection and isolation.The first proposed solution, a fault detection method based on dynamic principal component analysis, is complemented with a fault identification step based on a trajectory similarity measure, which is suitable for identifying the root causes of anomalies using the nearest neighbor classification principle. The results showed that the algorithm had good fault detection and fault classification capabilities in the presence of varying operating conditions and significant measurement noise (on the order of 1-5% of the fault signal magnitude). The method can be easily extended to monitor other systems if historical operating data or a process simulator is available, as soon as enough references are available to train the dynamic principal component analysis algorithm and to build the fault library. The possibility of combining risk assessment techniques and fault detection methods was investigated in the second proposed algorithm. A hierarchy of detectable anomalies in the monitored systems was established using a proposed risk priority number, thus supporting operators in prioritizing anomalous events based on the need for intervention. The results showed that the method was effective in separating high and low risk failure events, thus assisting the operators of the technology. The method can be easily extended to other technology systems, provided that sufficient historical data on the operation of the system and a failure mode and effect analysis as standard procedure is available. The third research point examined fault detection in distributed parameter systems. The aim of the investigations was to produce reduced models for the representation of chemical industrial systems that can adequately describe the spatial and temporal distribution of process variables characterising the system with an acceptably low computational demand to train fault detection schemes. The proposed approach for building reduced models can be easily extended to other chemical equipment if computational fluid dynamics models of their steady-state operation are available. Furthermore, the developed models not only allow for training fault detection schemes with lower computational requirements, but also provide a useful and computationally effective solution for analyzing chemical systems and performing sensitivity studies.

List of publications

Publications which form the basis of the doctoral dissertation

Publications in foreign journals

1. Tarcsay, B. L., Bobek-Nagy, J., & Egedy, A. (2022). Experimental and modeling based dead-volume detection for externally stirred tanks. *Chemical Engineering Communications*, *209*(6), 1-15. IF: 2.705 (2022), (Q2)

2. Tarcsay, B. L., Németh, S., Chován, T., & Bárkányi, Á. (2022). Development of CFD based Compartment Models for Analysing High Risk Processes. *Chemical Engineering Transactions*, *91*, 487-492. IF: 0.983 (2022), (Q3)

3. Tarcsay, B. L., Bárkányi, Á., Chován, T., & Németh, S. (2022). A Dynamic Principal Component Analysis and Fréchet-Distance-Based Algorithm for Fault Detection and Isolation in Industrial Processes. *Processes*, *10*(11), 2409. IF: 3.724 (2022), (Q2)
4. Bárkányi, Á., Tarcsay, B. L., Lovas, L., Mérő, T., Chován, T., & Egedy, A. (2024). Future of hydrogen economy:

simulation-based comparison of LOHC systems. *Clean Technologies and Environmental Policy*, *26*(5), 1521-1536. IF:4.748 (2023), (Q1)

5. Tarcsay, B. L., Bárkányi, Á., Németh, S., Chován, T., Lovas, L., & Egedy, A. (2024). Risk-Based Fault Detection Using Bayesian Networks Based on Failure Mode and Effect Analysis. *Sensors*, *24*(11), 3511. IF: 4.246 (2023), (Q1)

Publications in domestic journals:

6. Tarcsay, B. L., Bárkányi, Á., Chován, T., & Németh, S. (2021). Development of Compartment Models for Diagnostic Purposes. *Hungarian Journal of Industry and Chemistry*, *49*(1), 47-58.